A REVIEW OF LITERATURE ON THE THEORY OF VISUAL TARGET DETECTION PROBABILITIES

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THESIS

A Review of Literature on the Theory
of Visual Target Detection Probabilities

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September 1973

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1973

ABSTRACT

Information on visual target detection is widely scattered in the literature. This thesis presents a review and a categorization of current literature and provides a general discussion of representative models in the field of visual target detection. A literature research matrix is presented to aid the researcher in locating existing models which meet his requirements.

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I. INTRODUCTION

An important problem faced by the weapons system analyst is that of determining the hit or kill probability of a particular weapon system. However, in order to effect a hit or kill, the target must first be detected. For direct fire weapons, in particular, detection capability is a primary factor to consider in design as well as in the determination of tactics. For example, if detection range is not considered, the time and money spent developing a weapon system designed to kill at distances exceeding those at which targets can be detected is wasted.

The author's purpose in presenting a survey of the literature reflecting visual target detection probability models is to provide the system analyst with a convenient reference for a detailed study using models which are pertinent to the weapons system being investigated, and where possible, to eliminate redundant effort. The majority of the models discussed originated in technical memorandum and reports from various government agencies or activities and received only limited distribution. It is hoped that the consolidation and categorization of the models in this thesis will enable an analyst to more easily locate literature that is relevant to his particular needs. Secondly, this thesis will serve to familiarize the student or researcher with the terminology and assumptions related to visual target detection probability models.

Step by step procedures and techniques used by the authors of the models cited will not be discussed in detail since the interested reader can find the techniques and/or proofs used by referring to the original documents. This thesis focuses on the logical categorization of the models as to the way in which the models are formulated and the presentation of relevant models within the literature. A convenient categorization of the visual target detection probability models is illustrated in Fig. 1. The literature research matrix found in Section III is indicative of the wide range and diversification of content of current literature. In order to simplify the presentation; since terminology and symbology vary widely within the literature, all models presented in Section IV have been standardized so as to conform to the definitions found in Section II.

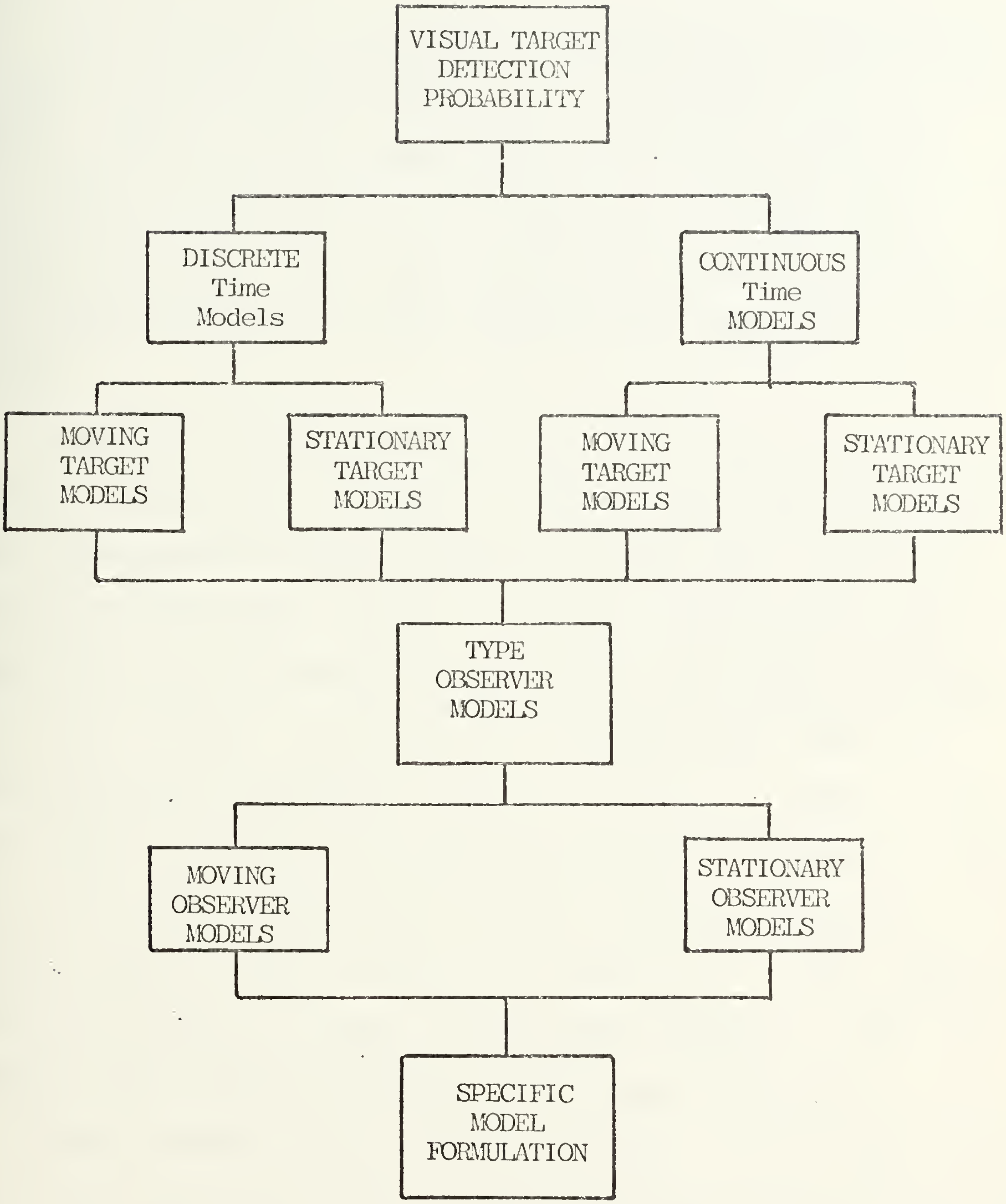
VISUAL TARGET DETECTION PROBABILITY
DISCRETE Time Models
CONTINUOUS Time MODELS
MOVING TARGET MODELS
STATIONARY TARGET MODELS
MOVING TARGET MODELS
STATIONARY TARGET MODELS
TYPE OBSERVER MODELS
MOVING OBSERVER MODELS
STATIONARY OBSERVER MODELS
SPECIFIC MODEL FORMULATION

Figure 1.

II. DEFINITIONS AND TERMINOLOGY

This section of the paper will present the basic definitions and terminology which are used throughout the presentation. Unless otherwise specified, the definitions and notations in this section will apply to all models and subject material within this paper and is consistent with military definitions (Sixth Quadripartite Conference on Armor, 1963).

Acquisition is an initial detection – recognition that the object detected is a member of a prescribed class of objects and the subsequent identification of particular characteristics of the object within its class. Detection is the indication of the presence of a target of potential military interest. Visual target detection probability, then, is defined as the probability that an observer is aware of the location of an object of potential military interest. Defining detection this way requires that an observer differentiate between objects that attract his attention. In this respect, military detection is more like recognition and is far more complex than the mere detection of a light stimulus.

Visual search is the process in which the eyes move around the visual scene in order to bring different parts of the scene into focus on the fovea of the eye.

Visual scanning can be thought of as an attempt to so align the detection lobe as to cause the target to fall within the lobe so that detection takes place.

As shown in Fig. 2, the detection lobe is that area, centered around the fixation axis and in the horizontal plane of vision, within which the glimpse probability has some value greater than zero. The lobe is sometimes referred to as a volume when three dimensional models are used but for illustrations the two dimensional concept will be used.

Scan or search pattern is a series of discrete detection trials or glimpses made by an observer to provide him with enough information to decide whether or not a target is present. The scan or search area is the area within which an observer searches for targets.

A glimpse is a fixation of the eye on a point in the background. With each glimpse there is associated a "glimpse" probability that the target will be detected on that glimpse given that a target is present at a certain fixed distance from the observer. This conditional probability is called the "glimpse probability."

Target detection time is the time expired from the instant the target first becomes visible and the weapon's crew is alerted. Detection time probability models describe the distribution of the time required by a single observer to detect a particular target (among those present in his environment) after this target has become intervisible to him. As concluded by an experiment conducted at Fort Benning, Georgia by the Human Resources Research Organization (HumRRO) in 1972 [Ref. 13] "The ability to detect human targets is significantly affected by the target's speed, the target's

THE DETECTION LOBE

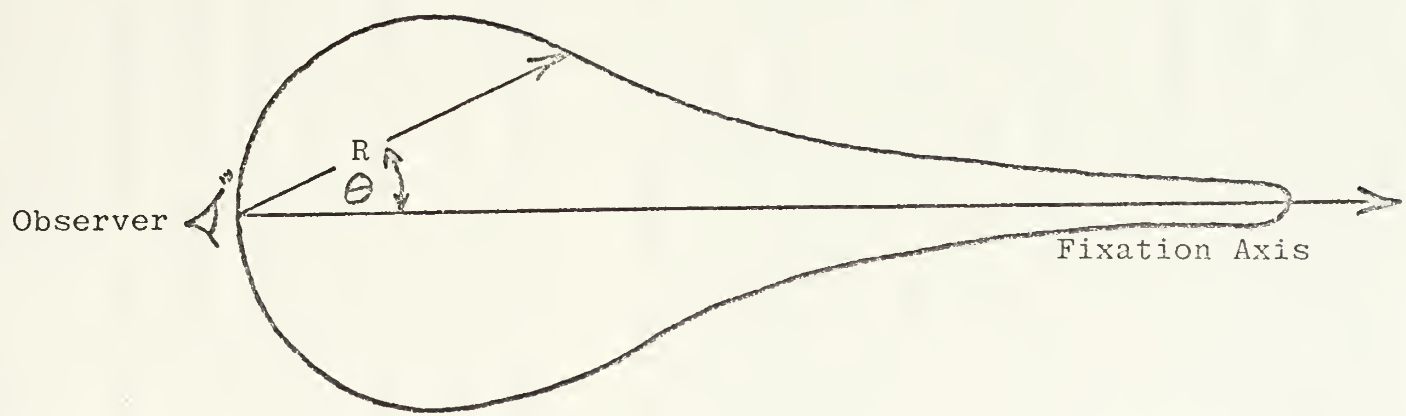

Figure 2

distance from the observer, and the complexity of the background in which the target appears." The terrain complexity and target range were found to be positively related with the time to detection, while target speed was found to be negatively related with the time to detection. Also, examination of the detection time distributions suggested that the probability distribution for the detection time distributions obtained was not exponential in form as is assumed in many studies.

Intervisibility is defined as the existence of an unobstructed line-of-sight (LOS) between the observer and any part of the target. For development of models, it is necessary that we assume either that once the target becomes intervisible it is completely intervisible, i.e., that all parts of it are intervisible, or that the portion of it that is intervisible does not change significantly after its initial appearance.

Luminance or brightness is the intensity of light (luminous flux) falling on a unit area and is usually measured in candles/m^2. Apparent luminance is a measure of luminance at some distance R from the object in question.

Inherent or intrinsic contrast is a dimensionless value determined by dividing the luminance of the object less the luminance of the background by the luminance of the background (all measured at zero distance).

Apparent contrast is similar to inherent contrast and is obtained by substituting apparent luminance for the word

luminance in the definition of inherent contrast. Instead of being measured at zero distance, however, the luminance is measured at some distance R from the object in question.

Meteorological range (V) is the range at which the contrast transmittance of the atmosphere is two per cent. This is the maximum distance at which large objects, such as mountains, can just be seen against the sky with the unaided eye.

Homogeneous background is a background that is uniform in its visual appearance and which does not contain forms which could be interpreted as targets. On the other hand, a heterogeneous background is a background that does not satisfy the condition of homogeneity. Such a background as this is termed a complex background because its visual properties, such as luminance and number and type of visual stimuli, vary markedly from place to place in its cross section.

A threshold for a particular stimulus is the least stimulus intensity that will produce a discriminatory response some set or predetermined percentage of the time. Thresholds are usually determined from a plot of percentage detections against the magnitude of change in stimulus intensity needed to produce a detection response. The classic resultant curve, called either an ogive or psychometric curve, is shown in Fig. 3. The psychometric curve in Fig. 3 is obtained by fitting the cumulative normal distribution to the data. The assumption is that the response to a stimulus

PSYCHOMETRIC CURVE

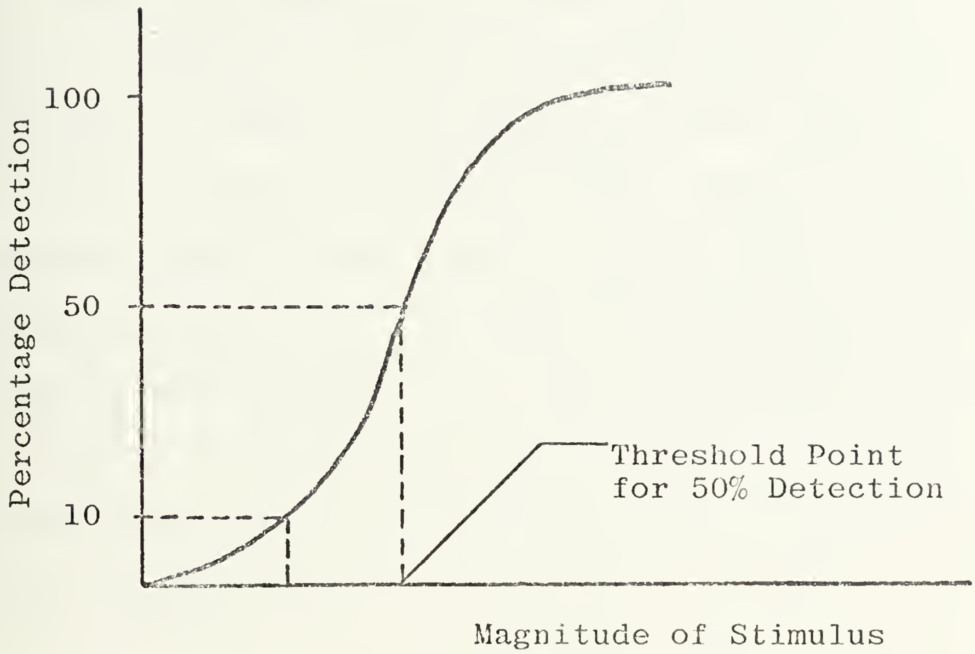

Figure 3

increment depends upon the operation of a multitude of minute factors which combine at random to help or hinder discrimination. The threshold is usually defined as the point where the frequency response is 50 per cent as shown in Fig. 3, however, B. O. Koopman in his work used the value 57 per cent. Contrast thresholds are most commonly used to describe the visual detection process. Other stimulus dimensions such as size, shape, and proximity to competing stimuli are usually held constant during experimentation to estimate contrast thresholds. The most appropriate ogive and its equation is determined for each set of experimental data by a procedure called the probit analysis which is explained in Ref. 10, pp. 6-10.

III. SUMMARY OF RESULTS OF LITERATURE SEARCH

To provide a reference guide to the numerous visual target detection probability models which exist within the current literature, a literature research matrix, Fig. 4, has been developed. While the author does not claim the references listed are a complete listing of all available material on the subject, these will reduce the set of models that the researcher needs to initially investigate when specific model characteristics are known. Many of the references listed include extensive bibliographies which will amplify the set of source material available.

It is not known to the author whether or not both a consolidation and categorization has been accomplished previously, although M. Moore has compiled a comprehensive bibliography of search and reconnaissance literature in which he reviews each of the references listed. Also, S. Pollock in Ref. 30 reviews an extensive list of references by considering the interfaces of search, detection, and action or decision. For this thesis, however, it was felt that a consolidation of the widely scattered material must also provide a categorization of the models if it were to be of any value. The literature research matrix is the vehicle by which the categorization is accomplished and is the primary difference between the two reviews by Moore and Pollock. In addition, this thesis is concerned primarily with detection models that can be used in combat

REFERENCES	DIMENSIONS			TIME FUNCTION		TARGET		OBSERVER		DATA	
	1	2	3	DISCRETE	CONTINUOUS	STATIONARY	MOVING	STATIONARY	MOVING	FIELD	LAB
1		x		x			x		x		x
2	x			x		x			x		x
3		x		x			x	x			
5		x			x		x		x		x
7			x		x	x			x		x
8		x			x		x	x		x	
9		x									
11		x			x		x	x			x
12		x			x		x	x		x	x
14		x		x	x	x	x	x	x		
17	x				x	x			x		x
19	x				x		x		x		
20		x		x	x	x	x	x	x		
21		x		x		x			x	x	
22		x			x	x	x	x	x		
24		x			x	x		x			
25			x		x		x		x		x
26		x			x		x		x		x
27		x			x		x		x	x	x
28		x		x	x	x	x	x	x	x	x
35		x			x		x	x			

Figure 4. Literature Research Matrix

models in which the researcher requires a certain amount of realism as in Refs. 19 and 24.

The research matrix in Fig. 4 lists five major categories or descriptors of visual target detection probability models. By listing the descriptors, a set of applicable models can be quickly located by the researcher. The five categories are: (a) dimensionality of the model; (b) type time function (discrete or continuous); (c) type target (stationary or moving); (d) type observer (stationary or moving); and (e) data check of model formulation (field or laboratory). The references listed are those found in the bibliography of this thesis. In order to use the matrix it is only necessary to locate the characteristic or set of characteristics which best describes the problem being investigated. The applicable references are then easily identified.

The first four of the five major categories or descriptors used in Fig. 4 should be obvious ones to the reader, however, the fifth category, data check or model formulation (field or laboratory), may not be so obvious. Experiments in psychophysics are most commonly performed in well controlled laboratory environments which are only abstract representations of actual or everyday environments. As a result, many of the experiments reviewed produce results which appear to be relatable only to the laboratory environment in which the tests were performed. This lack of correspondence between the two environments, laboratory and field, has been enumerated by S. Stollmack (1963) and is given in Table I.

TABLE I

A COMPARISON OF FIELD AND LABORATORY CONDITIONS

Factors	Laboratory Conditions	Terrain Conditions
1. Background -Color and Illumination	Homogeneous.	Non-Homogeneous.
-Dimensions	2-dimensional.	3-dimensional.
2. Cómpeting Stimuli	Some experiments use non-sense forms, most use none at all.	Many complex competing stimuli.
3. Temporal Conditions	The only changes made in the displays are usually the introduction of a target form.	The context of the visual scene is continually changing especially when the observer is in a moving vehicle.
4. Cues or Clues to target location	Some experiments have used discrete stimuli which, once detected, are clear in meaning. Interpretation of these clues most often involves a conscious evaluation of a specific stimuli.	Clues are always present but yet difficult to define. Terrain features, such as contour, may influence search direction, but the interpretation of the exact clue is not clear.
5. Targets	Observer is usually well aware of the physical appearance of the target stimulus.	Any one of a large class of targets may appear.
6. Motivation	Artificial	Life or death.

TABLE I--Continued

Factors	Laboratory Conditions	Terrain Conditions
7. Observer's Task	Detect the target.	Control vehicle, maintain communications with other observers, detect targets, avoid environment hazards, etc.
8. Time Frame	Well defined limits on the time within which the trial occurs.	Observer may be relatively unaware of the time frame during which the target will appear.
9. Display Limits	Area within which the target will appear is well defined.	Targets may appear anywhere in the terrain. Although a sector of responsibility may be defined, the possibility of being attacked from any position is likely to divert attention outside that sector.

Throughout the literature there are several basic documents which are used continuously as source documents for various papers and models. Many investigations have been made into the relationships between factors, listed in the next section, affecting visual target detection. Reference 14, Search and Screening, OEG Report No. 56, appears to be the foundation of many of the stationary target-stationary observer models. Using data from K. J. W. Craik and those from experiments at the Laboratory of Biophysics, Columbia University, B. O. Koopman derived an empirical law which describes the dependence of the threshold contrast on the visual angle subtended by a target at the eye and the angular distance from the center of the image on the retina to the center of the fovea. Koopman obtained an equation which allows the derivation of the detection range for a target of given area when contrast versus background and meteorological visibility range are known. The fundamental relationship found by Koopman seems reasonable and has often been used, however, various authors have attempted to revise Koopman's relationships by obtaining more accurate values for the parameters through laboratory and field experiments.

IV. RELATED MODELS

A. GENERAL

In this section models for the probability of visual target detection are discussed. The models are categorized by the type time function used to describe the detection process. Such a categorization minimizes the overlap between models and provides the researcher with a ready reference for a specific model. If a model can readily be extended to another category, it will be so indicated.

In general, the prediction of the visual detection range under various environmental conditions is of great importance for many military and civilian problems. This visual detection range is affected by various factors such as weather, meteorological visibility, brightness of the background, speed, altitude, and range, as well as human factors of training, experience, aptitude, visual acuity, adaptation and many others.

B. DISCRETE-PARAMETER MODELS

The event "detection" has been considered both as a discrete and continuous-parameter stochastic process by Koopman, 1957. He maintained that for the sake of model development, detection may be assumed to occur continuously in time or at discrete time intervals. The discrete search model assumes that an observer makes a series of brief glimpses or

fixations while searching. The model, as reported by E. S. Lamar in 1959, is an extension to Koopman's 1957 work.

Assuming the independence of the probability of detection on any one glimpse from past glimpses for $g_i (i=1,2,\ldots)$, Koopman pointed out in 1946 the following relation for P_n (the probability of a detection on any one of n glimpses)

$$P_n = 1 - \prod_{i=1}^{n} (1-g_i) \tag{1}$$

By assuming that the g_i are equal and constant, it follows that

$$P_n = 1 - (1-g)^n \tag{2}$$

and that $$\bar{n} = 1/g \tag{3}$$

where $\bar{n}$ is defined as the expected number of glimpses needed to make a detection. In 1959, E. S. Lamar formulated the search lobe concept (Fig. 2) in order to calculate the glimpse probability. As discussed in Section II, the probability of detection is 1.0 within the lobe and zero outside the lobe. The lobe shape accounts for the fact that targets at extreme ranges can only be focused on the fovea of the eye, but at less than extreme ranges the targets may be seen peripherally or off the fovea. θ in Fig. 2 is defined as the angle about the visual or fixation axis within which the target can be seen. R is the corresponding range within which the target can be seen for all angles equal to or less than θ. Any target which falls within the lobe during a fixation will be seen and any target which falls outside will be missed. Actually, the boundary of the detection lobe is

not as sharp as shown in Fig. 2. Some targets just outside the boundary may be seen and others just inside the boundary may be missed. However, since they compensate for each other it is assumed that the sharp boundary exists.

In order to use the lobe concept for predicting the glimpse probability of a human observer a relationship between R and θ is needed which will describe the shape of the lobe for any given set of experimental condition. Using data provided by the laboratory of Biophysics, Columbia University and investigations conducted by K. J. W. Craik at Cambridge, England during World War II, Lamar obtained the following equation from which detection lobes can be computed:

$$C = \begin{cases} 1.75\ \theta^{\frac{1}{2}} + 45.6\ \theta R^2/A & (0.8° < \theta < 90°) \\ 1.57 + 36.5R^2/A & (\theta \leq 0.8°) \end{cases} \tag{4}$$

where C is the target contrast taken as the absolute value of the difference in brightness between target and background, divided by background brightness and expressed in per cent, θ the angle off the visual axis in degrees, R the range in nautical miles, and A the projected area of the target in square feet. Equation (4) served a useful purpose at the time, however, R. H. Blackwell and others have obtained much better data. Also, two other variables have been neglected in Equation (4). These are background brightness and target asymmetry. Under daylight conditions of illumination neither is of any great importance and due to many other additional uncertainties characteristic of operational situations, can be neglected for all practical purposes.

In order to make Equation (4) operationally useful it must be transformed. That is, the contrast C is re-expressed in terms of intrinsic contrast C_o and meteorological visibility V in accordance with Koschmieder's Law, see pp. 2-5, Ref. 15. Then the equation is rearranged in terms of R_o/R where R_o is the foveal range under conditions of unlimited visibility. R_o is the value of R obtained by setting $\theta = 0.8°$ and $C = C_o$ in Equation (4). Finally, two new variables are introduced to ease the computation, F and G and the following equation is obtained

$$\theta = F(\sqrt{G/F + 1} - 1)^2 \tag{5}$$

where $F = 0.49(R_o/R)^4/(C_o - 1.565)^2$

and $G = 0.80C_o(R_o/R)^2 \exp(-3.44R/V)/(C_o - 1.565)$

Once these building blocks are developed, the next step is to incorporate them into Koopman's Equation (2). This can be done by superimposing the detection lobe on a search area as in Fig. 5 by assuming that: (1) a target is located at range R from the observer within the limits of the search area (between A and D), (2) the target angle θ is a random variable uniformly distributed over the whole search area, (3) the search direction for the ith glimpse is a random variable distributed uniformly between B and C, and (4) the shape of the detection lobe is constant as it moves over the entire search area and is independent of the previous glimpses. Thus, as long as the shape of the detection lobe remains constant as it moves over the search area, the probability of

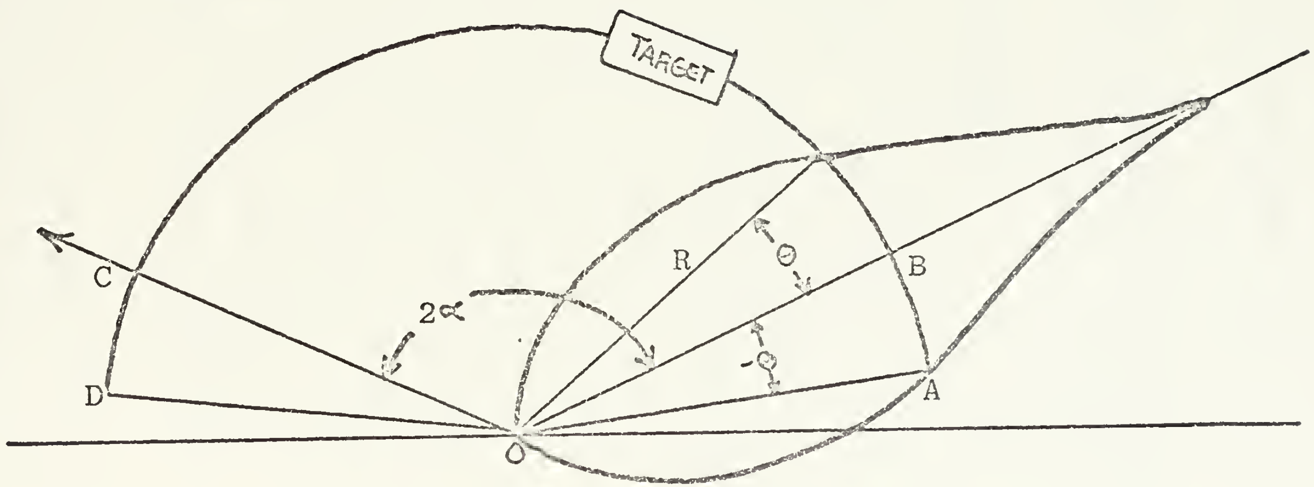

Figure 5. Detection Lobe Superimposed on Search Area

detection of a target at range R on any one glimpse is the ratio of the arc length within the detection lobe to the total arc length covered during the move over the search area. The following equation is obtained:

$$g_i = \theta/(\alpha + \theta) \qquad (6)$$

which in turn can be used in Equation (2) to obtain the probability of detection of a target on any one of n glimpses.

C. CONTINUOUS-PARAMETER MODELS

Koopman's continuous model assumes that the observer scans the search area continuously. This is so, not because the eye can see during movements between fixations, but because the events that combine to make a detection possible, such as the correspondence of the search direction with the target location, can occur at any time during the search. As noted before, Koopman's discrete model assumes that observers will search for the targets by sequentially fixating on various points in the background. Also, it is assumed that the time for each fixation is constant. Therefore, the model that is the most convenient to use and which gives the closest approximation determines whether to use the discrete or continuous model formulation.

In the model considered by Koopman, γ is called the instantaneous probability density (of detection) or, in other words, the detection rate. In addition, $\gamma\ dt$ is the probability of detecting a target in a short time interval dt. The quantity γ depends on the physical conditions such as the range to the target, the amount of illumination and haze, and the

size and brightness of the target compared to the background (Koopman, 1946). It then follows from the above that

$$P(t) = 1 - e^{-\gamma t} \tag{7}$$

by assuming that what happens in the time interval (t, t + dt) is independent of what happened in the time previous to t. P(t) in this equation is defined as the probability of detecting a target at any time up to and including time t. From Equation (7) it is apparent that

$$\bar{t} = 1/\gamma \tag{8}$$

where $\bar{t}$ is the expected detection time. Koopman then investigated the case where the probability function changes over time. For this case he used the following expression for P(t):

$$P(t) = 1 - e^{-\int_0^t \gamma(t)dt} \tag{9}$$

Here, $\gamma(t)$ is defined the same as γ was above, but in this case $\gamma(t)$ is allowed to take on different values over time. Koopman also points out, however, that P(t) does not necessarily approach 1.0 as t increases and

$$P(t) < 1 \quad \text{when} \quad \int_0^\infty \gamma(t)\, dt < +\infty$$

In this case $\bar{t}$ is not defined. Koopman's model was developed to derive optimum search procedures for the Navy and no evidence of verification of its predictive capacity for free search has been reported in the literature. His development makes no allowances for non-uniform target distributions or factors, such as clues, which might influence search behavior

on the part of the searcher. Koopman assumed that the dependence of γ on time t, expressed as $\gamma(t)$, is due to the fact that the range R to the target is changing as the observer is moving towards or away from the target. In addition, he made no allowances for any change in the function due to observer variables such as learning or vigilance and the route that the observer takes to the target is not considered as an important factor. Koopman also assumed that the type of route to the target chosen, as well as the particular section of the ocean's surface would not affect the function $\gamma(t)$. This assumption may be justified for search at sea since the backgrounds at sea do not change significantly as position and direction change over a fixed area of the ocean's surface. In ground search problems, however, both the area and the type of route used would have an important effect on the function derived for the following reasons: (1) Starting at some arbitrary point and advancing towards the target, the time at which a detection is made may include periods of time during which the target was not intervisible to the observer. For example, if a target is detected at time t_1 on one route and t_2 on a second route these points could not be used for the same function because while it might be that $t_1 = t_2 = 10$ seconds, the first route might exclude intervisibility for the first nine seconds while the second route had full intervisibility from all points along the route. (2) Important detection variables such as clues, contrast, and illumination vary from route to route

and area to area. Therefore, the route must be included explicitly in a ground detection model. Also, the data that is collected on one route is not necessarily usable on another route.

E. S. Lamar was working for the Navy in the same group and at the same time as Koopman. Lamar developed an expression for g in the discrete case based on threshold values. He determined that the probability g is proportional to the threshold angular distance θ_o of the target from the visual axis, and is inversely proportional to the angle θ subtended by the linear locus L of target positions:

$$\bar{g} = \frac{2.36\ \theta_o}{\theta} \tag{10}$$

He found it expedient to modify Equation (10) in order to derive an expression for the continuous case. If dt is an interval of time which is short compared with the time taken for the observer and target to change relative positions by an appreciable amount, and short also in the sense that the chance of a detection is small, but large in comparison to the time of a single fixation (about $\frac{1}{4}$ second), it is alright to consider γ dt, the probability of detection between the epochs t and t + dt. When dt = $\frac{1}{4}$ second, γ dt = g, then $\gamma = 4g$, or

$$\gamma = \frac{9.44\ \theta_o}{\theta} \text{ (time measured in seconds)} \tag{11}$$

Equation (11) was derived for "Linear scan." Lamar also derived an expression for area scan and obtained

$$\gamma = \frac{\theta_o^2}{\Omega} 4M(\theta_o, \alpha) \quad \text{(time in seconds)} \tag{12}$$

where the target is located in a region of a plane, subtending the solid angle Ω square degrees, α = the visual angle and

$$M(\theta_o, \alpha) = 2\pi \int_0^\infty f \left(\frac{1.75\theta_o^{\frac{1}{2}} + \frac{19\theta_o}{\alpha^2}}{1.75\theta_o^{\frac{1}{2}} \lambda^{\frac{1}{2}} + \frac{19\theta_o}{\alpha^2}} \right) \lambda \, d\lambda \tag{13}$$

Thus, Lamar was able to express γ in terms of θ_o which can be considered the visual perception angle.

Using a slightly different approach, M. E. Franklin and J. A. Whittenburg in 1965 conducted research on visual target detection in order to develop an air-to-ground target detection/identification prediction model based on the literature and data available at that time. Their survey of the literature, which included approximately 535 references, resulted in the selection of 24 variables which they thought were important enough to be included in a target detection/identification model. This list of 24 variables was further reduced by Franklin and Whittenburg to eight which are: target size, target shape, target/ground brightness contrast, clutter, terrain, altitude, range, and speed. Since in most operational situations variables interact to affect performance, a composite variable approach was used in their study. The eight primary variables were further grouped into three composite variables — target apparent size, target distinctiveness, and exposure time. The target apparent size, S, is

determined by the primary variables, target size, altitude, and range, with the latter two variables combined as slant range. Thus, the apparent size of the targets in square mils can be determined using the formula $S = \left(\frac{3000}{D}\right)^2$ where A is the target area in square yards and D is the slant range in feet. Target distinctiveness C, based on contrast, was determined for the preliminary model by use of colored pictures of the targets. Exposure time is the total amount of time that a target is in the observer's field of view and could be detected if the observer looked at the target. Combination of the three composite variables into the preliminary model was done using trial-and-error graphic procedures. Five out of the many possible ways that the variables could be combined were selected and tested. Table II shows the five combinations tested and the correlation ratio (η) of each combination with probability of detection/identification. Taking the fifth equation which has the highest correlation and substituting into

$$P_{TDI} = 1 - e^{-.0167 S_e} \tag{14}$$

where P_{TDI} = probability of target detection/identification, and

$$S_e = \sqrt{S}\, CT_e \tag{15}$$

the slope of the line in Fig. 6 is obtained. The graph in Fig. 6 shows the best fitting line for this combination of variables plotted against probability of detection/identification for the Whittenburg data obtained in 1959.

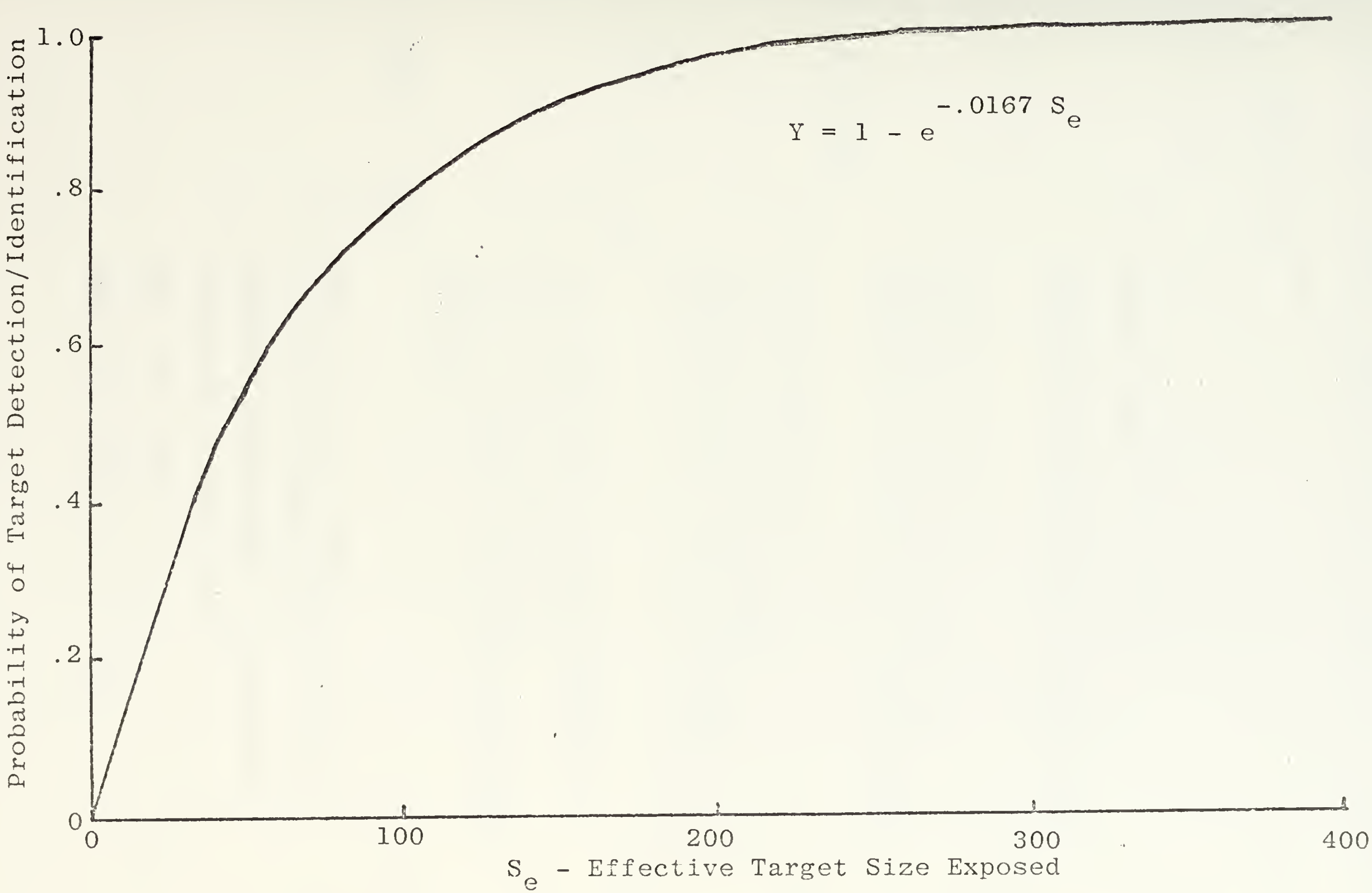
Probability of Target Detection/Identification
1.0
.8
.6
.4
.2
0
0
100
200
300
400
$Y = 1 - e^{-.0167\ S_e}$
S_e - Effective Target Size Exposed

Figure 6.

TABLE II

CORRELATION BETWEEN COMBINATIONS OF COMPOSITE VARIABLES AND DETECTION/IDENTIFICATION PROBABILITIES

Combination	Eta (η)
$S_e = ST$, where	
S_e = effective target size exposed	.66
S = maximum target apparent size	
T = effective exposure time (total time adjusted for probability of line-of-sight)	
$S_e = \bar{S}T$, where	.69
$\bar{S}$ = average apparent size	
T = effective exposure time (total time adjusted for probability of line-of-sight)	
$S_e = \bar{S}CT$, where	
$\bar{S}$ = average apparent size	.75
C = target distinctiveness value	
T = effective exposure time (total time adjusted for probability of line-of-sight)	
$S_e = \sqrt{\bar{S}}\, C\ (T/5)$, where	.85
$\sqrt{\bar{S}}$ = the square root of average apparent size	
C = target distinctiveness value	
$T/5$ = effective exposure time (total time divided by 5 and adjusted for probability of line-of-sight)	
$S_e = \sqrt{\bar{S}}\, CT_e$, where	.87
$\sqrt{\bar{S}}$ = the square root of average apparent size	
C = target distinctiveness value	
T_e = effective exposure time = T_s adjusted for probability of line-of-sight: when Total time/5 > 1, $T_s \geq 1$; when Total time/5 < 1, $T_s < \sqrt{T/5}$	

D. MOVING TARGET MODELS

A model more complex than the simple discrete or continuous parameter models described in Sections B and C above results when the observer and target are moving over the ocean, on the ground, or in the air in their respective paths, which may be either straight or curved and at either constant or changing speeds. The continuous change in their relative position constantly changes the instantaneous probability of detection. In this case it is necessary to deal with the functions g(t) and $\gamma(t)$ and calculate the probabilities of detection by means of Equations (1) and (9). In Fig. 7 the target is moving along path C with velocity v with respect to the observer. Koopman in his 1946 work determined that g(t) for the discrete case and $\gamma(t)$ for the continuous case become functions of the target location. Hence, the probability of detection according to Equations (1) and (9) become either

$$P(t)_c = 1 - \prod_{i=1}^{n} \left[1 - g(\sqrt{(x(t_i))^2 + y(t_i))^2})\right] \qquad (16)$$

or

$$P(t)_c = 1 - \exp\left[- \int_{t'}^{t''} \gamma(\sqrt{(x(t))^2 + (y(t))^2})\, dt\right] \qquad (17)$$

where t' = time when the target is at (x_o, y_o) and t'' = time when the target is at (x,y). The final result that Koopman obtains for the continuous-parameter model is

$$F(C) = \int_C \gamma(r)\, ds/v \qquad (18)$$

and for the discrete-parameter model is

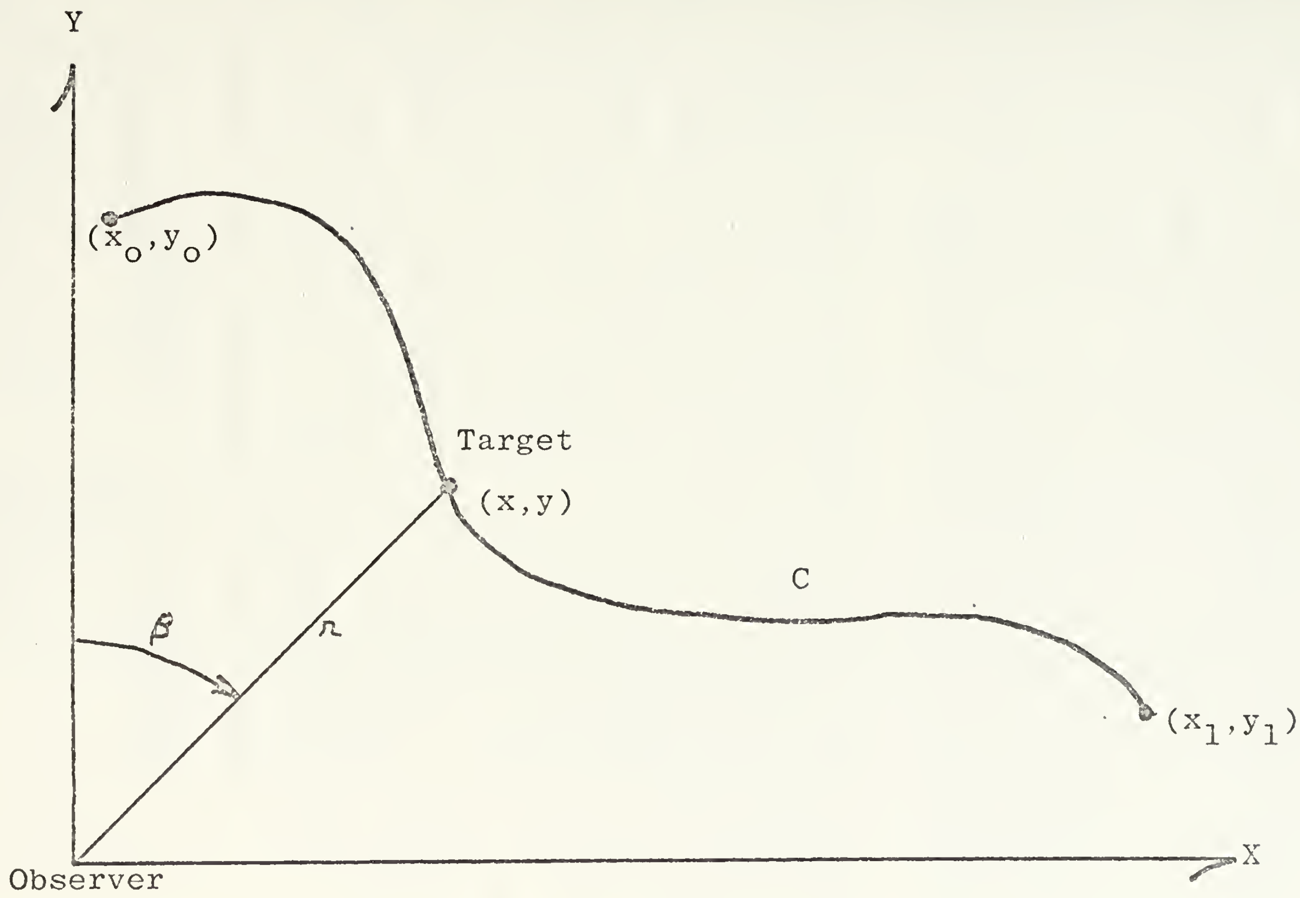

Figure 7. Target's Relative Track

$$F(C) = - \sum_{i=1}^{n} \log \left[1 - g\left(\sqrt{(x(t_i))^2 + (y(t_i))^2}\right) \right] \qquad (19)$$

where r is range to target, v is relative speed of the target to the observer, s is length of arc of C from (x_o, y_o) and F(C) is called the "sighting potential." Thus, Equations (16) and (17) can be combined into

$$P(t)_c = 1 - e^{-F(C)} \qquad (20)$$

where F(C) is given by either Equation (18) or (19) depending on whether the continuous-parameter or discrete-parameter model is used.

Koopman expanded his discussion to "A most important case . . . " in which both the observer and the target are moving at constant speed and course. As shown in Fig. 8, Track C becomes a straight line, and the speed v is a constant (as long as C does not change). In this case, x is the lateral range and the equations of motion are x = constant, y = vt, where t is measured from the epoch of closest approach, and where the positive direction of the y-axis is that of the target's relative motion. The "sighting potential," F(C), is given by one of the appropriate formulas below.

$$F(C) = - \sum_{i=1}^{n} \log(1-g(\sqrt{x^2+v^2 t_i^2})) = - \sum_{i=1}^{n} \log(1-g(\sqrt{x^2+y_i^2})) \qquad (21)$$

$$F(C) = \int_{t'}^{t''} (\sqrt{x^2+v^2t^2})\, dt = \frac{1}{v} \int_{y'}^{y''} (\sqrt{x^2+y^2})\, dy \qquad (22)$$

where y_i is the distance of the target at the ith glimpse to

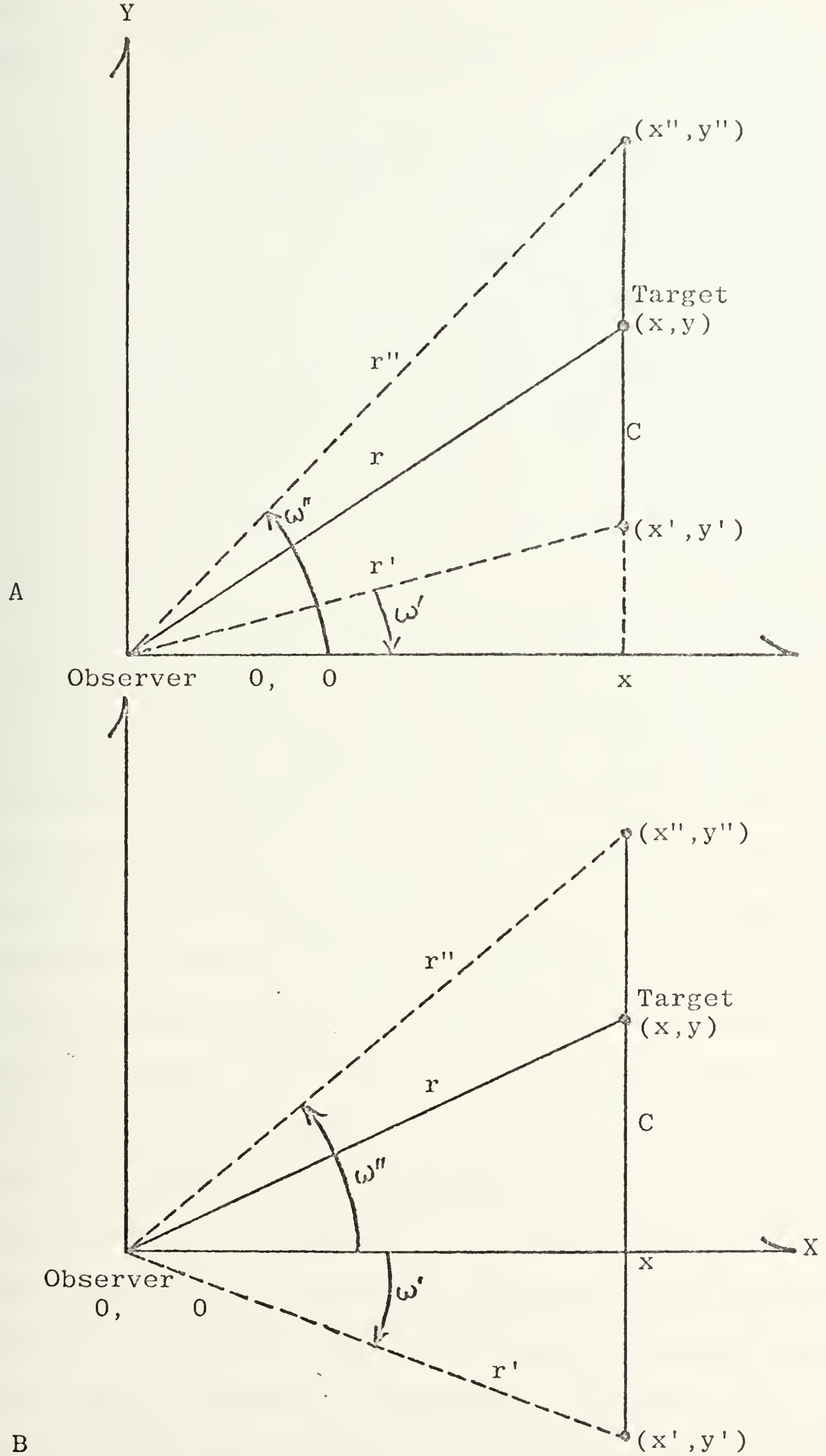

Figure 8. Detection at Fixed Speed and Course

its closest position, and (x',y') and (x'',y'') are the extremities of C: $x' = x'' = x = \text{constant}$, $y' = vt'$, and $y'' = vt''$.

E. S. Lamar expanded on this work of Koopman and attempted to fit some data obtained from World War II to determine how accurate a model it was. In Lamar's model, the glimpse or fixation time, T, was included and had to be set equal to 1.65 seconds instead of the more accepted range of values of 0.071 to 0.50 seconds with 0.25 seconds being used the most. This factor of approximately six has serious implications for the military. In the Navy's case it would mean six lookouts in place of one.

As mentioned throughout this thesis, much of the early work done on visual target detection was done by researchers at O.E.G. such as Koopman and Lamar. The theory that they developed was directed at solving naval sea search problems where backgrounds are relatively homogeneous. The theory is based on the relation of detectability to contrast using threshold concepts which are not clearly defined for heterogeneous backgrounds and illuminations found common to ground search problems. In addition, the theory assumes that the target location is uniformly distributed over the entire search area which may be appropriate for sea searches, but for ground searches it appears to be unduly restrictive. It is just good tactics to emplace troops and weapon systems in covered and concealed positions whenever possible and to cover likely avenues of approaches into one's position. As a result, it will be very rare if the targets will be uniformly

distributed over the entire search area or sector of responsibility. Another assumption of the Koopman models that is also restrictive when applied to ground models is that of assuming that the direction of the observer's fixation at any time t is a random variable with a uniform probability distribution over the entire search area. Experimental evidence indicates that this assumption is not representative of the observer's behavior in heterogeneous background situations. Once again, this assumption relates to the orientation of naval sea searches. In the ground search case, clues, likely avenues of approach, peripheral vision, and warnings from other observers may influence the direction of the fixations. Stollmack in his 1965 work developed a model of the ground-to-ground detection process for tank weapon systems by removing the restrictive assumptions of Koopman's models.

V. AREAS FOR FUTURE RESEARCH

Areas for future research in visual target detection probability modeling are open in both the theoretical development of the models and in the application of existing models for the evaluation of specific weapons systems. Most of the components of mathematical models are based on empirical laws. Since all of these laws are not well established, the models cannot be considered satisfactory in every sense. When developing their models, most authors make an attempt to find and understand the interrelationships of the important factors influencing the visual detection ranges. However, a number of contributory effects remain to be studied in detail before such models can be fully exploited.

First of all, there are discrepancies between indoor and outdoor test results. Most laboratory results are obtained under ideal conditions. In some cases, there are considerable discrepancies between laboratory test results. Therefore, there is a need to conduct more field tests in order to confirm the empirical laws and parameter values used in the mathematical models.

Because of their high costs, field tests are not carried out in great numbers. In most of the field tests many parameters of interest have either not been recorded in a satisfactory way or they have not been determined in a quantitative sense. Better preparation of the tests would have given a

great deal more information without appreciable increase in the costs. A few well-prepared field tests could contribute much and help to establish a well-founded semi-empirical theory. Models should be designed in such a way that the empirical laws used can be readily replaced. It can thus be updated, improved or extended in one direction or another when more reliable data from other studies becomes available.

Another area for future research is that mentioned by S. Pollock in Ref. 30 where he states that "There has been a tendency to model the three phases of search, detection, and action separately. . . ." That is, each phase is modeled independently and the result or outcome of one model may be used as input in another. The interfaces of these elements are often neglected or assumed away in many studies and approaches and thus many realistic results based on this interplay of factors are lost in the model. Models should be developed and experiments devised to account for this fact.

The analyst should also consider the problem that incorporates false alarm signals which are usually present in most everyday life situations. Research should be carried out to determine the effect of false alarms on visual detection theory and measures of effectiveness of weapon systems.

Another assumption that may be suspect is that of independent glimpses which Koopman assumed in his continuous-parameter model. It appears that, in many ground-to-ground combat situations, the assumption that detection on successive looks or increments of time is independent of what occurred on

previous looks or in previous increments is unrealistic since the observer may receive many clues to the presences of a target or to the target's location. This fact is apparent when the ground commander places his observation posts (OP's) to cover likely avenues of approach into his sector of responsibility. Thus, a model that fails to include this feature in it may not actually model the "real world."

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		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles Richard Macchiaroli		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE September 1973
		13. NUMBER OF PAGES 47
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
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Visual Target Detection

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Information on visual target detection is widely scattered in the literature. This thesis presents a review and a categorization of current literature and provides a general discussion of representative models in the field of visual target detection. A literature research matrix is presented to aid the researcher in locating existing models which meet his requirements.

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